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A 3 million year index for North African humidity/aridity and the implication of potential pan-African Humid periods

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ABSTRACT

Mediterranean sediments are valuable archives of both African monsoon variability and higher-latitude climate processes, and can also be used to provide an environmental context for early human migrations and settlements. However, the long history of Mediterranean palaeoclimate studies largely pre-dates the advent of widespread x-ray fluorescence (XRF) core-scanning, so there are few continuous and high-resolution geochemical records from this key region that extend beyond the last glacial cycle. Here we present XRF core-scanning results for ODP Site 967 (Eastern Mediterranean) that have been fully-calibrated into element concentrations spanning the last 3 million years (My). Comparison with independent geochemical data from conventional XRF highlights disparities for certain element/element ratios, thus suggesting the need for caution when taking ratios of scanning XRF data. Principal component analysis of the calibrated XRF dataset reveals two dominant components: detrital inputs (PC1) and a 'sapropel' (≈monsoon run-off) signal (PC2), which we use to establish a new orbitally-tuned chronology. We observe inverse covariation between PC2 and a previously published aeolian dust record from ODP Site 967 (Larrasoaña et al., 2003), and combine these records to produce a composite index of humidity and aridity for the wider North African region over the past 3 My. We propose that by combining run-off and dust signals in a single metric, our index captures the effects of both strengthening/northward migration (increased run-off) and weakening/southward retreat (increased dust) of the North African monsoon. Comparison of the index with published records of Northwest and East African palaeohumidity suggests that it tracks the timing of "Green Sahara Periods" throughout the Plio-Pleistocene, and that at least 30 of these intervals coincided with increased humidity across East Africa. We tentatively suggest that these specific episodes may be termed "pan-African Humid Periods", as a means to highlight large-scale climate trends and to provide an environmental framework for palaeoanthropological research.

1. Introduction

The Eastern Mediterranean is a particularly desirable region for palaeoclimate studies due to its sensitivity to both high- and low-latitude climate processes (Woodward, 2009), and its pivotal location for early human migrations and civilisations. On orbital timescales, strengthening and northward migration of African monsoon precipitation during boreal summer insolation maxima results in substantially increased freshwater run-off into the Eastern Mediterranean (e.g., Rossignol-Strick et al., 1982; Rohling et al., 2002, 2004; Osborne et al., 2008). Conversely, desertification of the Sahara and Northern Africa when the monsoon rainbelt lies further south causes increased dust deposition in Eastern Mediterranean sediments (Larrasoaña et al., 2003). Sea-level changes at these timescales are also registered in the basin (Rohling et al., 2014), due to the sensitivity of Mediterranean $\delta^{18}O$ to reduced exchange with the Atlantic Ocean (Rohling and Bryden, 1994).

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The sensitivity of the basin to African monsoon variability has broader implications, as it provides a well-preserved archive of humid intervals in North Africa, and thus an essential environmental context for archaeological/anthropological research. The most recent of these intervals – the Holocene 'African Humid Period' (Ritchie et al., 1985) – is documented by widespread continental evidence in addition to marine proxy records (see Drake et al., 2013; Larrasoaña et al., 2013; and references therein); three more "humid" intervals within the last glacial cycle are also fairly well-documented. However, for older intervals, the timing and extent of such 'Green Sahara periods' (GSPs) becomes increasingly poorly constrained due to a lack of well-preserved continental deposits with tight chronostratigraphy, and an equal lack of high-resolution marine records. Consequently, the timing of older GSPs is often based on a sequence of organic-rich deposits ('sapropels') in the Eastern Mediterranean, which reflect deep-water anoxia and increased primary productivity when monsoon-driven run-off reached the basin (Rossignol-Strick, 1985; Emeis et al., 1996; Rohling et al., 2015). Yet sapropels can be partially or even totally oxidised by post-depositional redox processes (e.g., Higgs et al., 1994; Thomson et al., 1999; De Lange et al., 2008), so the occurrence and/or timing of GSPs based on this approach may be inaccurate if oxidised or 'ghost' sapropels are not fully identified. Knowledge of GSPs is crucial for understanding the possible timing and routes of early human migrations and settlements (e.g., Osborne et al., 2008; Drake et al., 2010; Rohling et al., 2013; Timmermann and Friedrich, 2016), especially in conjunction with a growing body of evidence for relatively humid intervals within East Africa over the last few million years (see Maslin et al., 2014).

Given the significance of the palaeoclimate archive contained in Eastern Mediterranean sediments, there is a conspicuous lack of continuous, high-resolution records of bulk element geochemistry from this region that extend beyond the last glacial cycle (~130 ka). For example, geochemical studies of older (>130 ka) Eastern Mediterranean sediments have either focussed on sapropels/limited time intervals (e.g., Passier and De Lange, 1998; Wehausen and Brumsack, 2000; De Lange et al., 2008) or used a relatively low sampling resolution (e.g., Calvert and Fontugne, 2001). Scanning x-ray fluorescence (XRF) records spanning 0–1.7 Ma from the distal Nile Fan were discussed by Zhao (2011), but those records have not been calibrated into element concentrations so the signal may be ambiguous. High-resolution Ti/Al records from ODP Sites 967/968 have been published for the 0–1.4 and 2.2–3.2 Ma intervals (Wehausen and Brumsack, 2000; Lourens et al., 2001; Ziegler et al., 2010; Konijnendijk et al., 2014).

We address this issue by presenting scanning XRF records from ODP Site 967 for the past three million years (3 My) at ~0.3 ky resolution. We use a multivariate log-ratio calibration (Weltje et al., 2015) to convert the scanning XRF data into element concentrations, and then perform a principal component analysis on the calibrated XRF dataset (section 3). We find that the first principal component captures detrital inputs to ODP Site 967, while the second principal component represents a sapropel (hence monsoon run-off) proxy. We use our sapropel/run-off proxy to establish an orbitally-tuned chronology, which we evaluate against previous chronologies for this site (section 4). Finally, we present a new index of humidity/aridity for the wider northeastern Saharan/North African region over the past 3 My, based on our sapropel/run-off proxy and a previously published (Larrasoaña et al., 2003) aeolian dust record from the same site.

2. Methods

ODP Site 967 (34° N, 34°E, 2252 m water depth; hereafter, 'ODP967') is situated on the Eratosthenes seamount and was drilled during ODP Leg 160 (Emeis et al., 1996) (Fig. 1). A new composite depth splice was established (Supplementary Table 1) so that our chronostratigraphy could be based as much as possible on the sampled core sections. This ensured that depth/age uncertainties associated with adjusting 'off splice' samples to the composite splice were minimised. Konijnendijk et al. (2014) also published a composite-depth splice for ODP967. However, that splice is partly based on ODP Site 968, and it doesn't cover the lower 45 m of our studied interval. All previous results from ODP967 discussed in this study have been converted to our new composite depth scale.

2.1. X-ray fluorescence (XRF)

Approximately 90 m of the archive halves of ODP Site 967 cores were scanned at 1 cm intervals at Marum – Center for Marine Environmental Sciences, University of Bremen (Germany) on a third generation Avaatech XRF core scanner. Core sections were covered with 4 μm-thick Ultralene film and measured at 50 kv with a 1 mA current and Cu filter, and then at 10 kv with a 0.5 mA current and no filter; a 20 s count time was used for both runs. To convert the scan 'counts' into element concentrations, 40 bulk sediment samples of ~2 cm^3 were taken from selected working halves equivalent to the scanned archive halves. Samples were chosen to cover a range of lithologies (e.g., sapropel, clay, sapropel-clay intergrades) based on the XRF scan results, as well as a range of depth intervals. The samples were air-dried and ground with an agate mortar and pestle. Single element concentrations were determined on the sediment powder samples by energy-dispersive polarisation XRF (EDP-XRF) spectroscopy using a PANalytical εpsilon3-XL instrument at the University of Bremen. High quality control of the EDP-XRF measurements was based on more than 60 certified and in-house standard reference materials (e.g., MAG-1; Govindaraju, 1994). The measured values were within 1% of the accepted value for Al, Ca, Fe and K. Precision was always better than 0.4%.

2.2. Calibration of scanning XRF counts

Uncertainties in the output scanning XRF counts can be reduced by calibrating the scan data with a representative suite of discrete sub-samples from the same core, which have been analysed using a more quantitative geochemical technique. Calibration is also necessary if multivariate statistical analyses are to be performed on the scanner data. Element counts from the XRF scans were therefore converted into concentrations using a multivariate log-ratio calibration (MLC), following Weltje et al. (2015). This approach builds on the previously proposed univariate log-ratio calibration (Weltje and Tjallingii, 2008), but instead calibrates all elements simultaneously using centred log-ratios, thereby enabling elements that were not adequately captured by the scanning XRF (typically those with an atomic mass less than that of Al) to be taken into account in the calibration. This undefined variable is here termed 'everything else', hence the relative concentrations of all scanned elements and 'everything else' sums to 100%.

The predictive power of our calibration can be assessed by cross-plotting the reference concentrations with the MLC results (Supplementary Fig. 1). High r^2 values for all elements indicate a robust calibration, which is strongest for Ca and Sr ($r^2 = 0.93$) and weakest for Zr ($r^2 = 0.68$). Nonetheless, when considering the predicted concentrations over all depths, the calibration infers some anomalously high concentrations for Ba (>10,000 ppm) compared to results from conventional XRF analyses of ODP967 (<2000 ppm; this study and that of Konijnendijk et al., 2014). As the data are compositional, outliers in the calibrated XRF dataset were detected using the Mahalanobis distance (Rousseeuw and van Zomeren, 1990), which is specifically designed for